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## Summary of Rocketdyne Engine A5 Rocket Based Combined Cycle Testing



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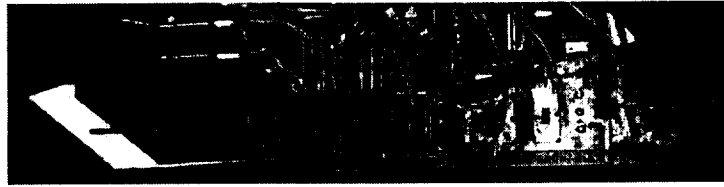
### Introduction

Rocketdyne Propulsion and Power (RPP) has completed a highly successful experimental test program of an advanced rocket based combined cycle (RBCC) propulsion system. The test program was conducted as part of the Advanced Reusable Technology program directed by NASA-MSFC to demonstrate technologies for low-cost access to space. Testing was conducted in the new GASL Flight Acceleration Simulation Test (FAST) facility at sea level (Mach 0), Mach 3.0 – 4.0, and vacuum flight conditions. Significant achievements obtained during the test program include 1) demonstration of engine operation in air-augmented rocket mode (AAR), ramjet mode and rocket mode and 2) smooth transition from AAR to ramjet mode operation. Testing in the fourth mode (scramjet) is scheduled for November 1998.

### Hardware Description

The Rocketdyne engine concept is a multi-mode combined cycle engine with a fully integrated air augmented rocket (AAR) mode for take-off static thrust. Following take-off and initial acceleration, the engine transitions to dual mode ramjet operation around Mach 3.0 and transitions to scramjet operation around Mach 5.0. Scramjet operation continues until Mach 10 – 12, at which time the rockets are restarted for final orbital insertion. The experimental hardware, designated Engine A5, is shown in **Figure 1**. The engine flowpath is a fixed geometry configuration for integration with the vehicle forebody and aftbody. The flowpath consists of a 3D internal sidewall contraction inlet, followed by a constant area isolator with provision for top wall boundary layer bleed. Installed in the isolator are the individual rocket motors. The rocket motors are integrated into vortex mixing ramps, which also contains main fuel injectors for ramjet and scramjet operation in the dump combustor. Sidewall fuel injectors located at the nozzle entrance provide additional fuel for AAR and ramjet operation. The engine nozzle top wall is contoured to integrate with the vehicle and the sidewalls provide efficient integration of side by side flowpath installations. Engine A5 provides actively cooled combustor and rocket hardware. Although water-cooled, the hardware uses flight-like design and manufacturing processes and demonstrates an important technology step towards flight experiments. In addition to the flight-like design and fabrication processes, the integral rockets have a wide mixture ratio range and deep throttle capability. This feature is critical to the multi-mode operation of RBCC engines, including smooth transition to ramjet operation. Over 200 static pressure taps, 10 heat flux gauges, 20 thermocouples, and 50 high-pressure transducers provide detailed data on facility and engine operation and performance. A dual, single axis, opposed load cell balance provides thrust measurement.

## Engine A5 Description



- **Water Cooled Flight-like Hardware**
  - Fixed Geometry Reduces Complexity and Weight
  - 3D Sidewall Compression Inlet Provides Self Starting with Benign Unstart Pressures
  - Vortex Mixing Used to Maximize Scramjet Performance
  - $M=10$  to 12 Pull-up Reduces Risk
- **High Performance Rocket Motors Integrated into A/B Flowpath**
  - GH2 and GOX Injectors Designed for Deep Throttle and Wide Mixture Ratio Capability
  - Multiple Fuel Stations Employed to Optimize Mode Performance

Figure 1

## Test Summary

An extensive test program has been completed on the Engine A5 hardware and is summarized in the **Figure 2**. To date, a total of 82 tests have compiled over 1600 seconds of engine operation. A number of important technology demonstrations have been achieved in the course of this testing. The engine has been successfully operated in three of the four propulsion modes. In the AAR mode, twenty-one tests were conducted at Mach 0 (sea level static conditions) and an additional 15 tests at Mach 3.0-4.0 flight conditions. The tests were conducted over a wide range of mixture ratio ( $MR = 2.0 - 11.0$ ) and rocket chamber pressure (100 – 1200 psia), and when combined with upstream and downstream fuel addition, demonstrated the effects on thrust augmentation, base pressurization, inlet pumping, inlet starting, and nozzle separation. Over the course of the test program, the integral rockets logged an impressive 400+ ignitions and 4700+ seconds of operation. In the ramjet mode, twenty-one tests investigated performance and operating characteristics of the flowpath over the Mach 3.0-4.0 range. In addition to thrust and specific impulse, the effect on inlet/combustor interaction, isolator performance and inlet unstart/restart characteristics for fuel scheduling at different injector locations were also evaluated. The third mode tested was rocket only propulsion at near vacuum conditions. In this series, ten tests provided a database that investigated the effects of rocket chamber pressure, mixture ratio and base pressurization. Results demonstrated the high performance rocket specific impulse required for the RBCC flowpath. The final test series consisted of eleven trajectory tests and utilized computer controls to provide simultaneous variations in flight conditions and fuel schedules. The control of both flight profile and engine fuel schedules

provided the ability to demonstrate a complete mode transition from AAR to ramjet under accelerating flight conditions. This achievement demonstrates one of the key technologies of the ART program (i.e. mode transition in true flight conditions) and is a significant step in advancement of the technology readiness levels (TRLs) required for flight experiments.

### **Engine A5 Test Summary**

- **82 Tests Completed to Date in the FAST Facility**
- **Engine A5 Tested in 3 of 4 Propulsion Modes**
  - Sea Level (AAR Mode)
  - “Flown” from M=3-4 (AAR and Ram Modes)
  - Vacuum (Rocket Mode)
  - M=5-8 Scram Testing Planned for November
- **AAR to Ram Mode Transition Demonstrated**
- **Significant Rocket Motor Operational Details**
  - 4700+ sec of Operation
  - 400+ Successful Ignitions
  - Deep Throttle Capability Proven:  $P_c=100-1200$
  - Wide Mixture Ratio Variation Demonstrated:  $MR=2-11$
  - 33 Tests at or above Stoichiometric Conditions

**Figure 2**

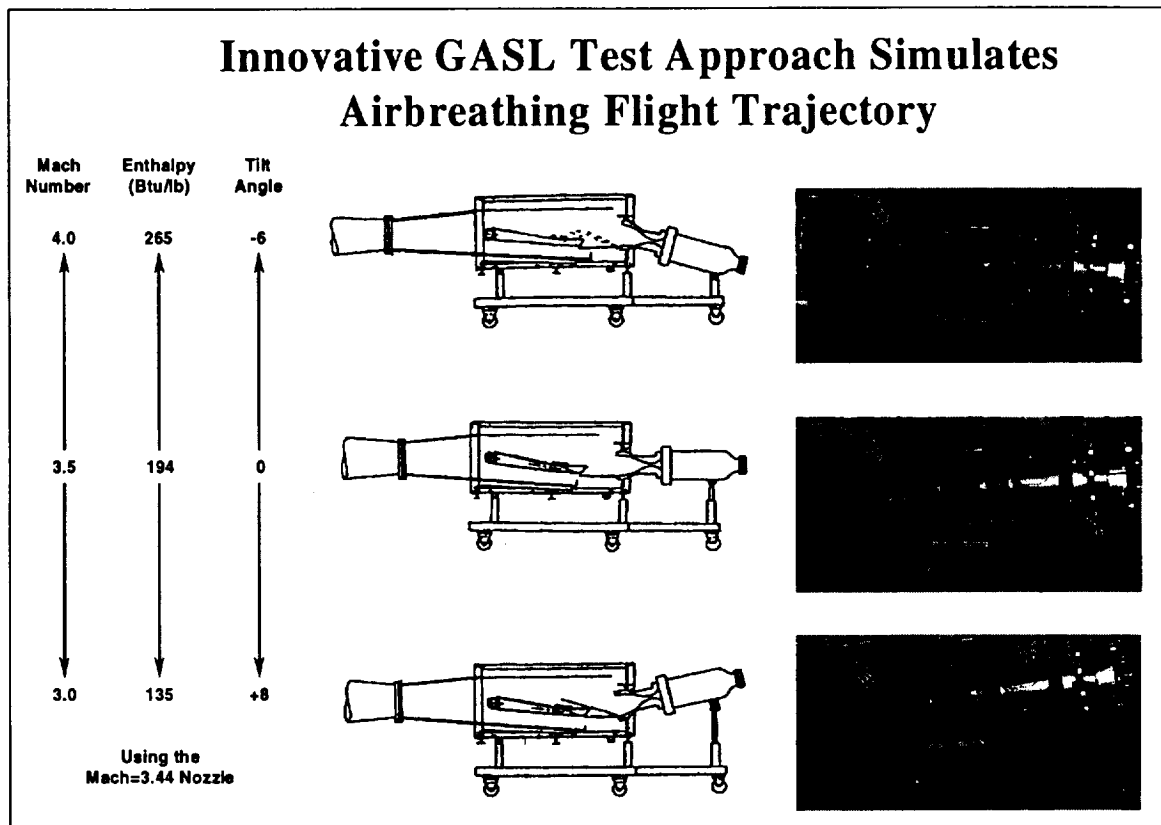
### **Flight Acceleration Simulation Test Facility (FAST)**

This testing effort focused on flowpath performance and operability testing at  $M=0$ , vacuum and across the Mach number range of  $M=3-4$ . The testing was conducted in the GASL FAST (Leg 5) facility. GASL, MSFC and Rocketdyne developed this unique trajectory simulation facility during the ART program. **Figure 3** illustrates the physical arrangement of the articulating facility nozzle that provides variation in the engine inflow Mach number during a test. This time-varying facility reproduces the environment experienced by the engine as it accelerates along the flight test trajectory. Changing the amounts of air, hydrogen and oxygen available for combustion in the vitiator produces variation in enthalpy. The oxygen mole fraction is maintained at 21% by adding excess oxygen to the vitiator. Varying the vitiator pressure reproduces the variable total pressure experienced in flight. Articulating the nozzle creates a compression shock or an expansion wave that varies the aerodynamic Mach Number. Exit flow from the nozzle was determined, during a calibration series<sup>1</sup>, to have a uniform profile at angles from +6 degrees (compression,  $M=3.2$ ) to -8 degrees (expansion,  $M=3.8$ ) for the Mach 3.4 nozzle.

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<sup>1</sup> “Shakedown and Mach 3 to 4 Calibration of the Flight Acceleration Simulation Test (FAST) Facility,” R. Engers, W. Swartwout, & R. Stone, GASL Internal Technical Report TR373, October 1998.

The two key advantages of the FAST facility are: a) permitting demonstration of mode transitions and b) significantly reducing the cost of testing, by providing the capability to test over a Mach number range in a single test instead of several tests.



**Figure 3**

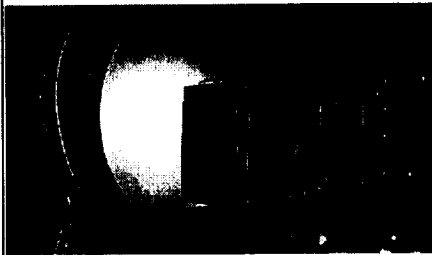
**Figure 4** shows Engine A5 installed in the FAST facility. The top photo illustrates how the engine sits between the facility nozzle/jet stretcher (on the far right) and the facility diffuser. The engine is attached to a metric, opposing load cell, thrust balance. A horizontal reflection plate runs the length of the engine to minimize losses in the external flow. External engine drag is kept to a minimum through incorporation of windscreens on the external engine surfaces. Trombone shaped feed lines are used to transfer the fluids to the engine and minimize thrust stand interference. The entire engine assembly, including instrumentation, is located inside the test cell. The test cell is closed for all tests except sea level AAR tests. The diffuser is directly attached to a 60,000 cubic foot vacuum sphere. This permits long duration testing (order of 30 sec) at significant flowrates.

The lower left photo shows the engine operation during a sea level AAR test. The exit plume is clearly visible as the hot, fuel rich, gases react with the ambient air. The lower right photo shows the engine operating during a vacuum rocket test. This picture is taken through one of the test cell windows. The plume in the vacuum rocket test is nearly invisible, as there is no air to react with the hot exit gas.

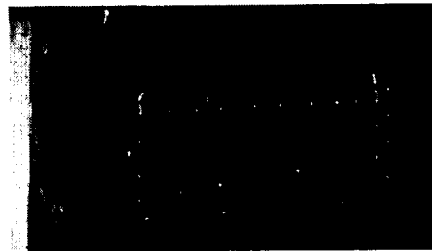
## Wide Versatility of FAST Facility Demonstrated w/ Engine A5



Engine A5 Installed in the GASL Flight Acceleration Simulation Test Facility (FAST)



Engine A5 Sea Level AAR Test



Engine A5 Vacuum Rocket Test

Figure 4

### Trajectory Testing

Engine A5 was operated on a trajectory producing results shown in **Figure 5**. The engine was transitioned from AAR to ramjet operation during the middle of the trajectory. With two modes of operation, mode transition, changing Mach number and dynamic pressure conditions, a large number of operating parameters are varied during this type of test. The end result is a very large quantity of engine operability data. These multiple figures provide understanding of the complexity of the test and the relative time of events. The plots on the left in **Figure 5** summarize operation of the facility. In this test the facility vitiator was started at  $t = 17$  seconds and reached initial operating pressure at  $t = 25$  seconds. At  $t = 36$  seconds the angle was set at 8 degrees and the total temperature was set to the corresponding enthalpy for this aerodynamic condition. From  $t = 36$  seconds until  $t = 57$  seconds the vitiator conditions were ramped to the high Mach number conditions. The rocket motors were started then throttled back on the trajectory and shut off when transition Mach number was reached. Acceleration through the trajectory was continuous as indicated by the increasing vitiator pressure and the decreasing vitiator angle. Following the rocket motor ramp to mainstage conditions, fuel was injected through the base bleed, the scram and the ram fuel injectors. Base bleed was increased during the AAR acceleration period. At transition to ramjet, the rocket motors were shut off simultaneously with a large increase in the ramjet fuel. Note the changes in all four fueling schedules in the  $t = 48$  second time frame when the engine is transitioning from AAR to ramjet operation. The parameter PS1203 is actually the rocket motor hydrogen supply; this pressure indicates the hydrogen burned in the rocket prior to  $t = 48$  seconds and after this time, the base

bleed through the motors. Ramjet and base bleed fuel were decreased and scramjet fuel was increased during the acceleration in ramjet mode to high Mach number condition.

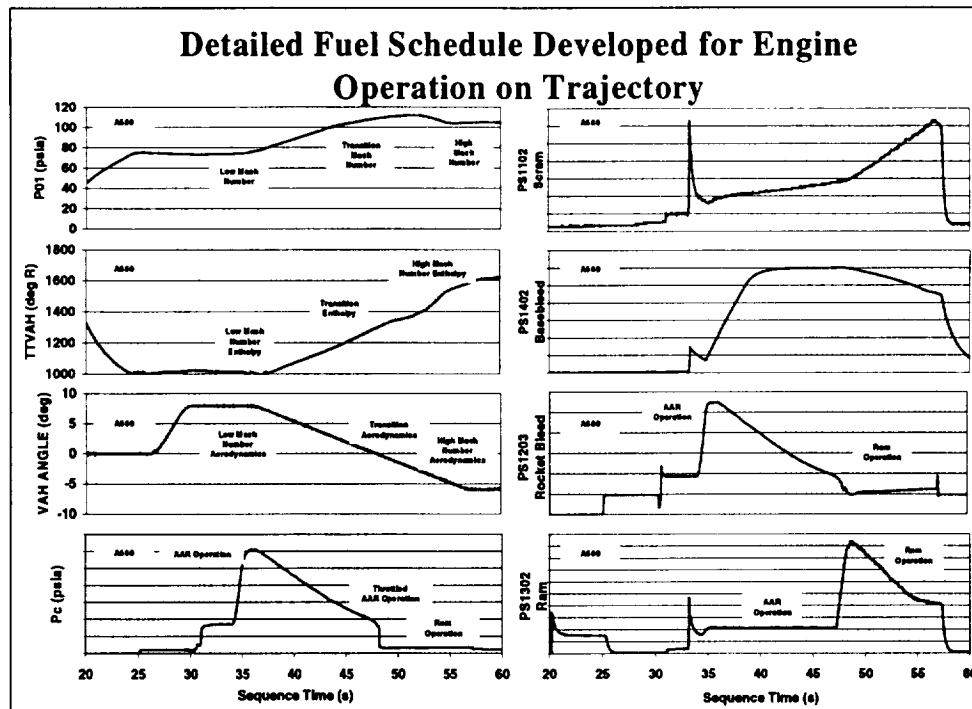


Figure 5

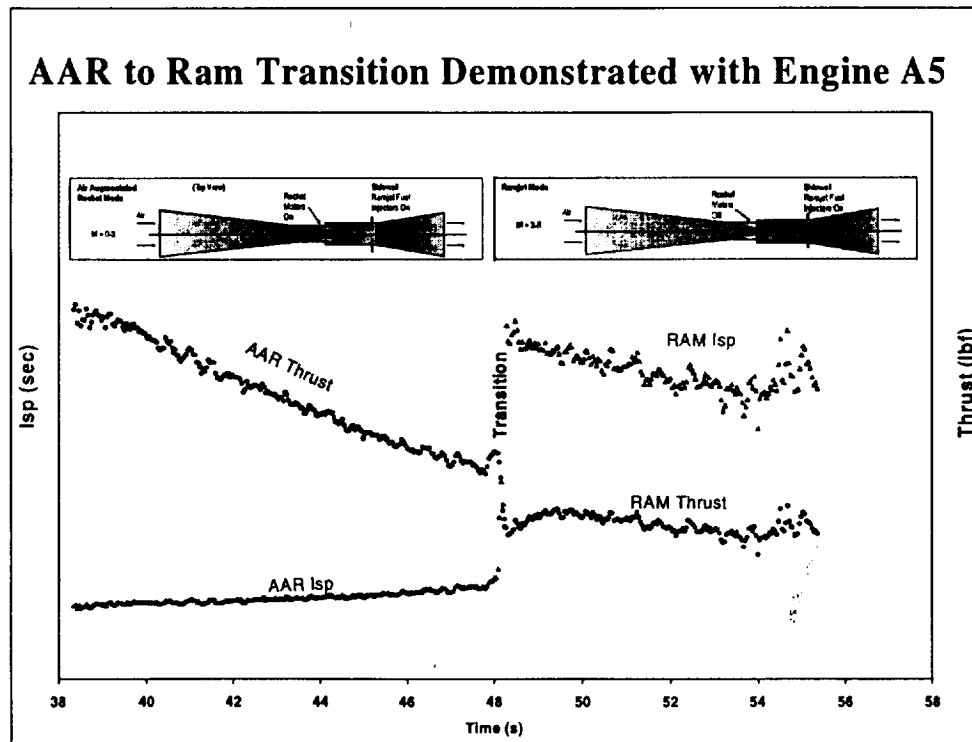


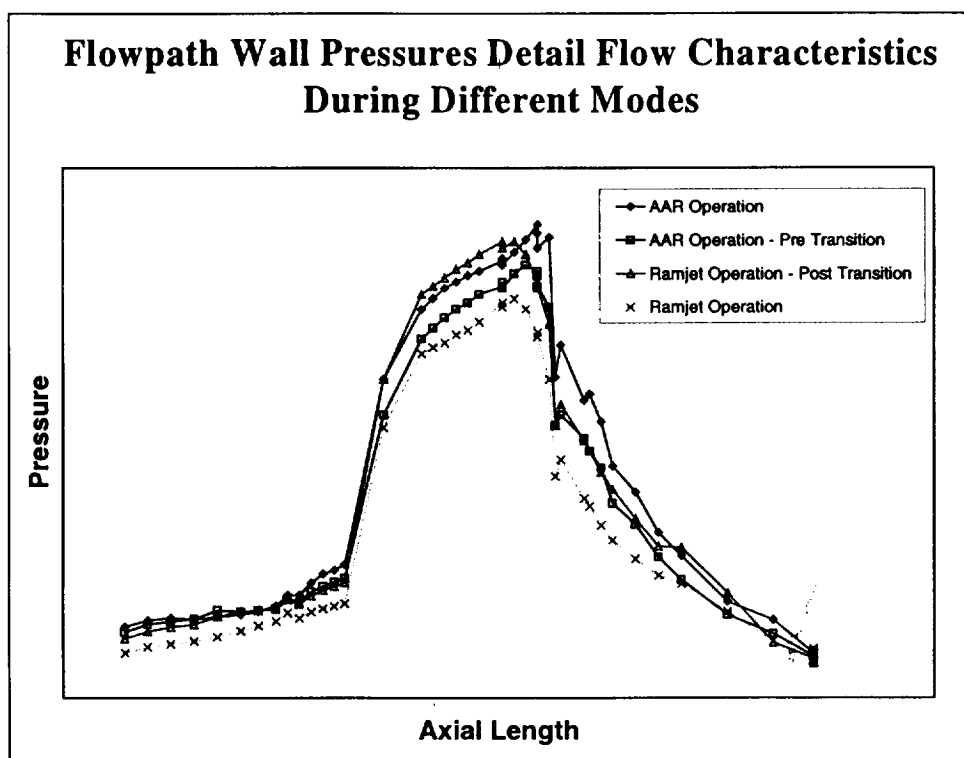
Figure 6

## Transition Demonstrated

**Figure 6** shows the results of the fuel schedule changes in terms of thrust and specific impulse (Isp). The rocket motors started a nominal chamber pressure at the low Mach number and were throttled to a low chamber pressure at  $t=48$  s, then shut off for the transition to ramjet operation. At this time, the thrust decreased from an AAR value to a ramjet value. The specific impulse, during transition, has a dramatic increase due to the sharp decay in oxygen flow. Ramjet thrust and Isp then remain steady until the end of the trajectory. A reasonably smooth transition from AAR to ramjet was demonstrated despite the fact that this was one of the initial tests. With refinements in base, scram and ram fuel injection this transition can be smoothed even further.

## Flowpath Wall Pressures

The top wall pressure profile illustrated in **Figure 7** provides an example of the extensive database collected from the test program. Data provided from the more than 200 pressure taps provide similar profiles for each of the four engine walls. The examples provided in **Figure 7** are from the trajectory test shown previously, which transitions engine operation from the AAR to ramjet mode. As indicated by the profiles, the transition from AAR to ramjet occurs with only minor changes in the actual engine pressure profile. The changes are due to the rocket motor throttling and changing engine fuel schedule required for transition. Also, the freestream flight conditions are changing to correspond to an accelerating constant flight dynamic pressure trajectory; thereby resulting in the lower inlet static pressure at higher Mach number.



**Figure 7**

## Summary

A significant step in the development of RBCC technologies has been demonstrated for the Rocketdyne fixed geometry lightweight propulsion system. The Engine A5 hardware has demonstrated good performance in AAR, ramjet, and rocket modes. Scramjet testing is scheduled in the current calendar year. The capabilities of the GASL FAST facility to test all engine modes in a single test cell, both statically and dynamically, provides important advances for the development ground testing needs of RBCC engines in the Pathfinder class. The modular Engine A5 hardware developed and tested under the ART program demonstrates the multi-mode engine concept and raises the flowpath TRL to 5 by testing in a relevant flight environment. Performance goals demonstrated to date are on target to meet Vision Vehicle (SSTO) requirements.

### Summary

- **FAST Facility Provides Ground Simulation of Flight Conditions from M=0-8**
  - Operationally Demonstrated M=0, 3-4 + Vacuum
- **Modular Engine A5 Demonstrated Critical Technologies**
  - Actively Cooled, Integrated Components
  - Demonstrated Multi-Mode Flowpath Operation
  - Dynamic Engine Operation - Smooth Mode Transition
- **Overall Test Program has Raised Flowpath TRL to 5 by Testing in Relevant Environments**
- **Performance Goals are on Target to Meet Vision Vehicle Requirements**

Figure 8



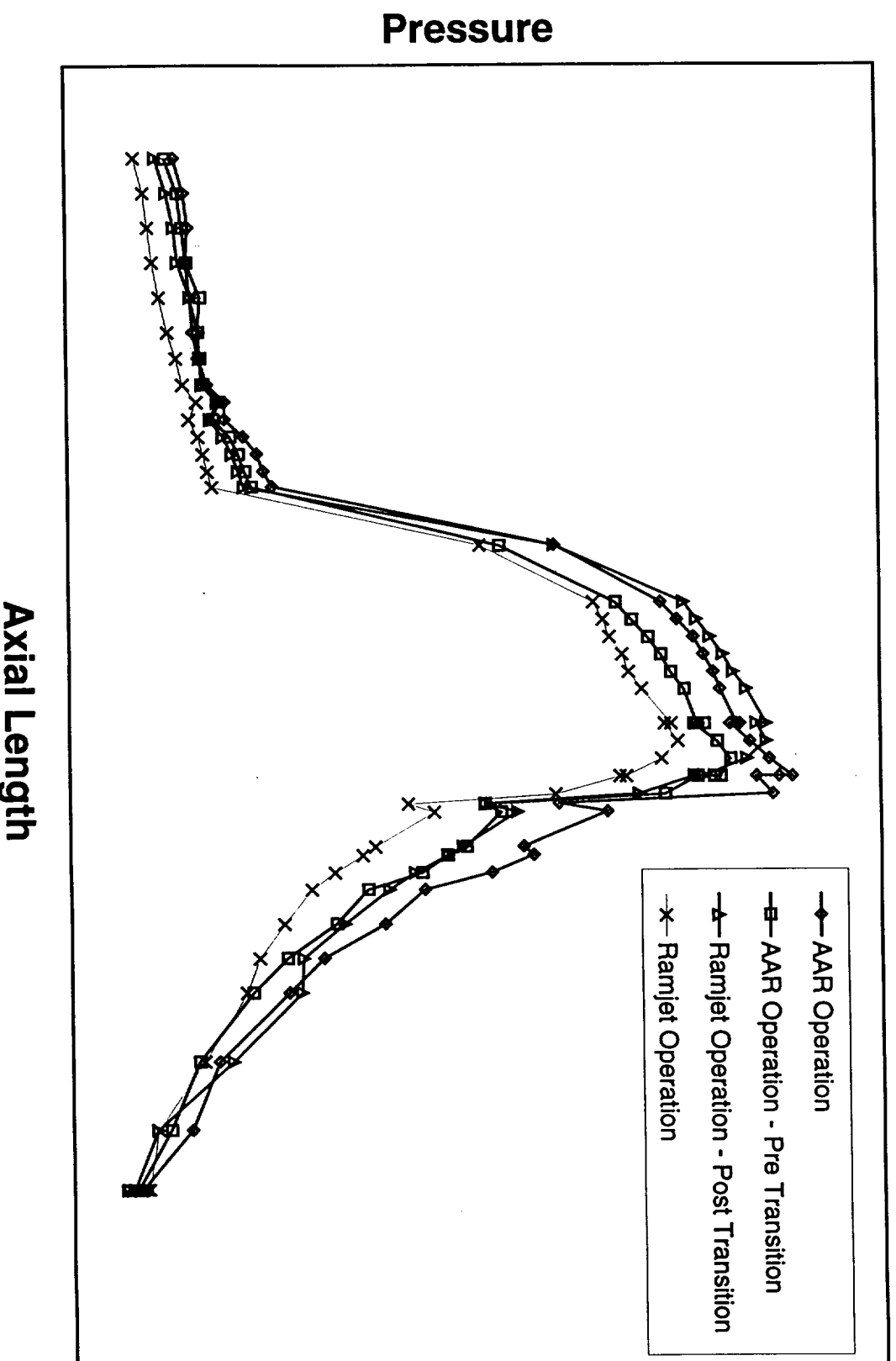
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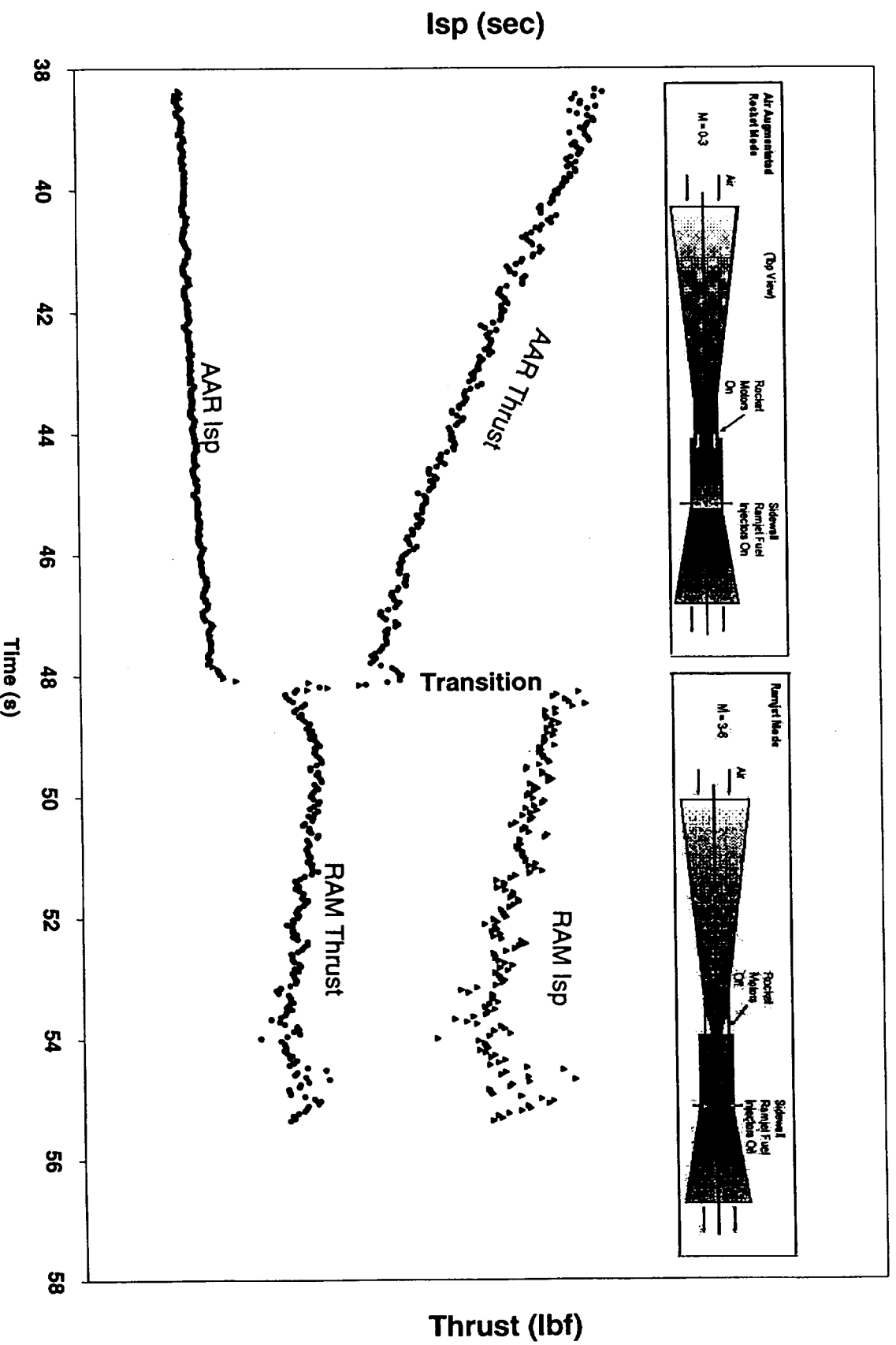
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# Flowpath Wall Pressures Detail Flow Characteristics During Different Modes



# AAR to Ram Transition Demonstrated with Engine A5



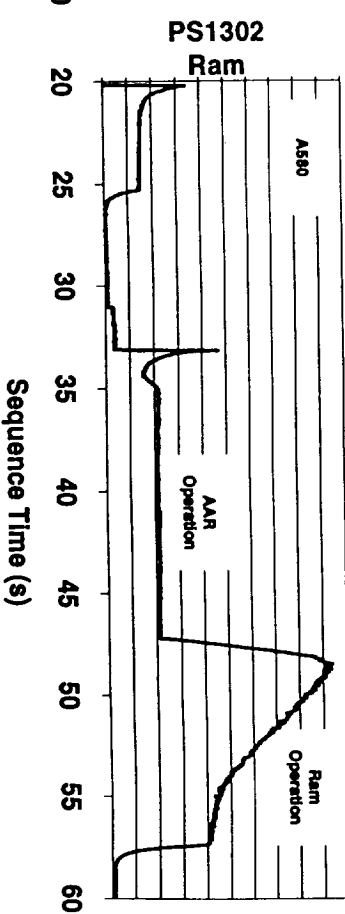
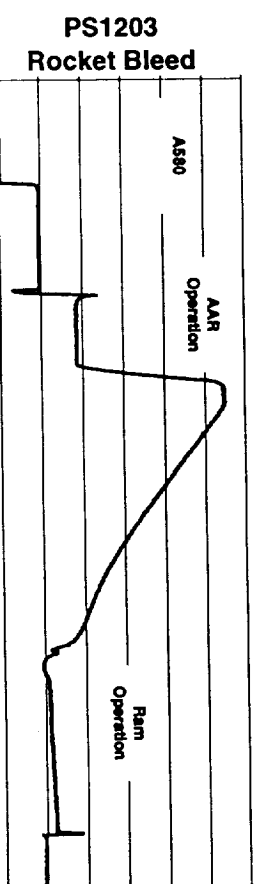
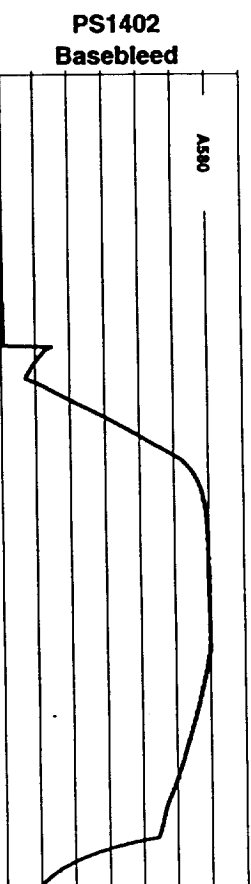
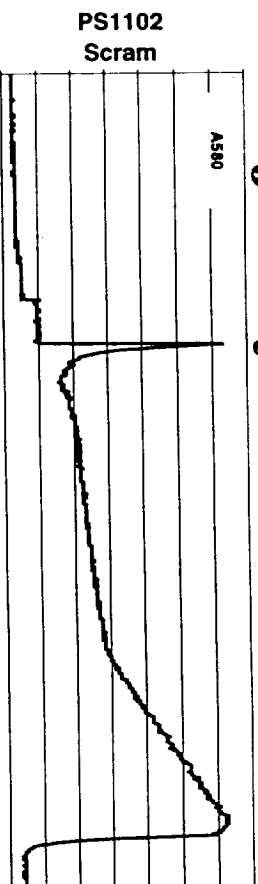
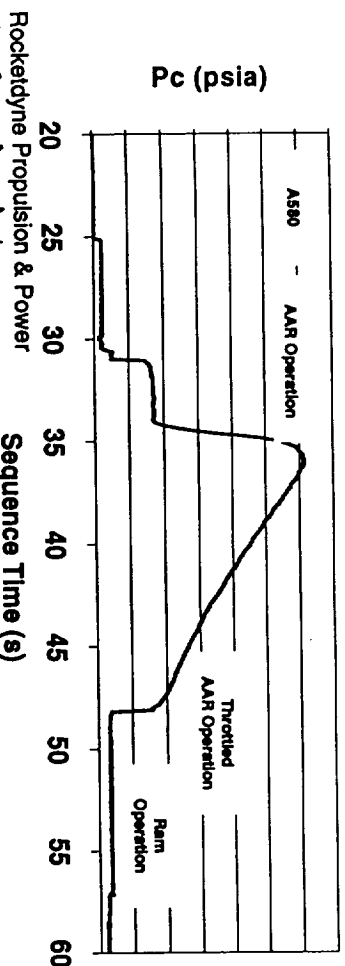
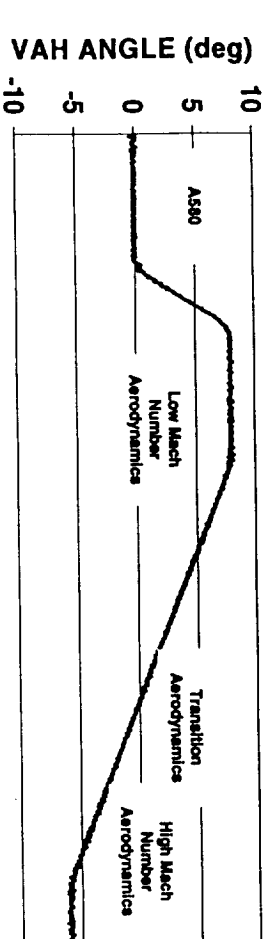
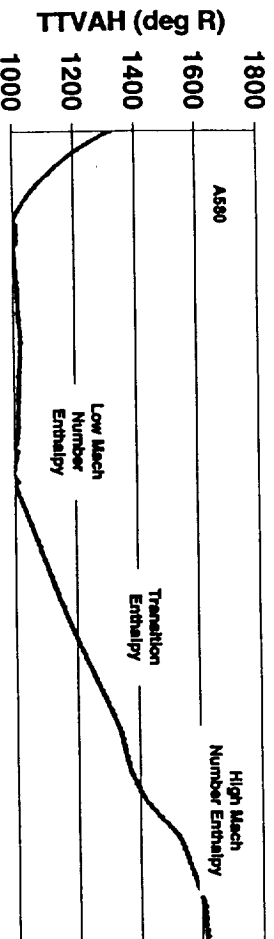
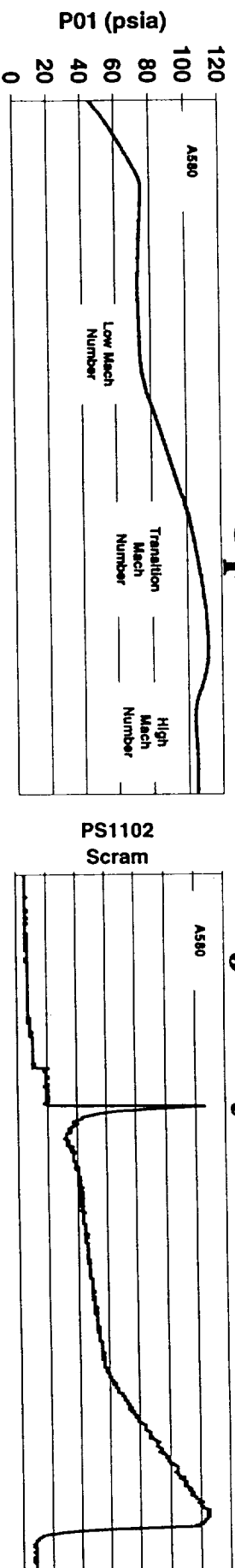
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**BOEING**

# Detailed Fuel Schedule Developed for Engine Operation on Trajectory



# Wide Versatility of FAST Facility Demonstrated w/ Engine A5



Engine A5 Installed in the GASL Flight Acceleration Simulation Test Facility (FAST)



Engine A5 Sea Level AAR Test



Engine A5 Vacuum Rocket Test

Rocketdyne Propulsion & Power

*Aerothermodynamics*

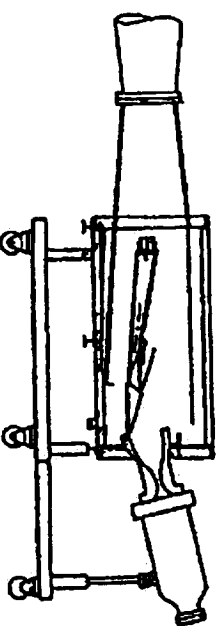
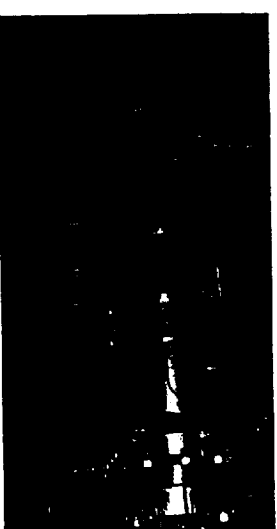
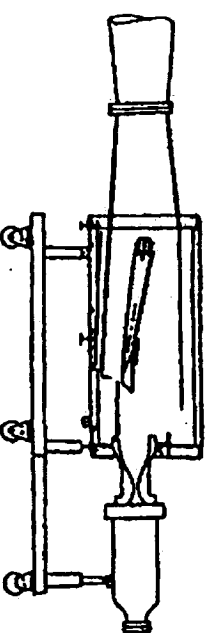
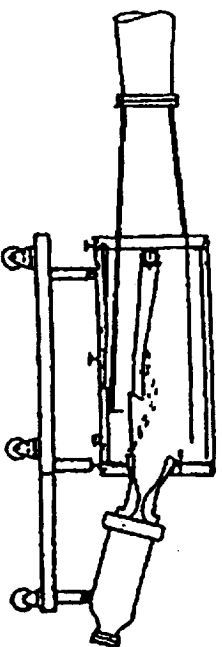
ROCKETDYNE  
CORPORATION

*BOEING*

# Innovative GASL Test Approach Simulates Airbreathing Flight Trajectory

Mach Number	Enthalpy (Btu/lb)	Tilt Angle
4.0	265	-6
3.5	194	0
3.0	135	+8

Using the  
Mach=3.44 Nozzle

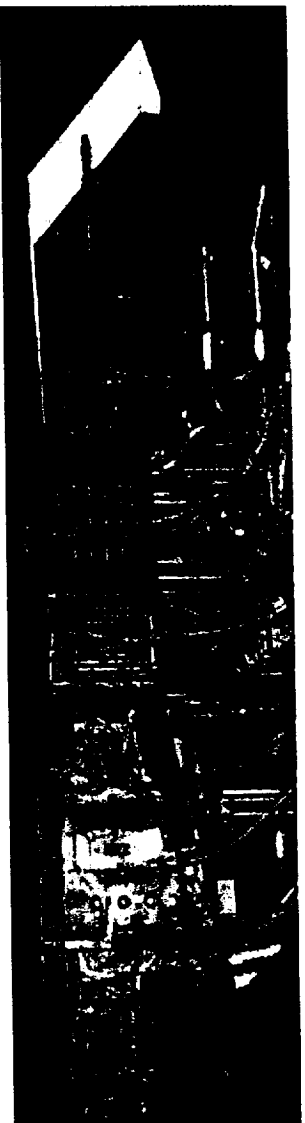


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